

Department of Electronic Engineering
ELE2EMI
Electronic Measurements & Instrumentation

1 Units and Accuracy

In all experimentation, analysis and reporting, it is essential to perform the work reliably, use appropriate units of measurement, and record the values accurately.

How much credence can be given to a set of results also depends on the correct assessment of the contributions of various sources of errors. These must be understood, and their deleterious effect on precision must be included in the results, either by explicit error estimates, confidence intervals, or by deciding on a sensible number of significant figures.

This lecture is based on material from chapters 1 and 2 of *Carr*.

1.1 Units

1.1.1 Metric Prefixes

Memorise these!

Metric Prefix	Name	Power of Ten
y	yocto	-24
z	zepto	-21
a	atto	-18
f	femto	-15
p	pico	-12
n	nano	-9
μ	micro	-6
m	milli	-3
c	centi	-2
d	deci	-1
		0
da	deca	1
h	hecto	2
k	kilo	3
M	mega	6
G	giga	9
T	tera	12
P	peta	15
E	exa	18
Z	zetta	21
Y	yotta	24

1.1.2 Units of Measurement

The next table lists *some* of the **units of measurement** useful to Electronic Engineers. Memorise these also!

Quantity	Unit	Symbol	Value
Frequency	hertz	Hz or H	s^{-1}
Velocity	metre/second		$m.s^{-1}$
Acceleration	metre/second-squared		$m.s^{-2}$
Force	newton	N	$kg.m.s^{-2}$
Energy	joule	J	N.m
Power	watt	W	$J.s^{-1}$
Electric Current	ampere	A	
Electric Charge	coulomb	C	A.s
Voltage	volt	V	$J.C^{-1}$
Electric Field	volt/metre		$V.m^{-1}$
Resistance	ohm	Ω	$V.A^{-1}$
Resistivity	ohm.metre		$\Omega.m$
Conductance	siemens	S	Ω^{-1}
Conductivity	siemens/metre		$S.m^{-1}$
Capacitance	farad	F	$C.V^{-1}$
Magnetic Flux Linkage	weber	Wb	V.s
Magnetic Flux Density	tesla	T	$Wb.m^{-2}$
Inductance	henry	H	$Wb.A^{-1}$

The unit **siemens** is named after *Werner von Siemens* who in 1847 founded a certain German company to build telegraph lines utilising his first major invention, the *pointer telegraph*.

1.1.3 SI units

Although there is a proliferation of units, of which the table above lists only a few, they are all abbreviations for products of powers of a few basic units. These *fundamental units* are prescribed in the SI (Syst'eme Internationale, also called the International System of Units) and mandated by the ISO (International Standards Organisation). These **SI units** are:

Quantity	Unit	Symbol
Length	metre	m
Time	second	s
Mass	kilogram	kg
Current	ampere	A
Temperature	kelvin	K
Amount of matter	mole	mol
Luminous intensity	candela	cd

Notice that the official unit of mass in the SI system is not the gram, but the kilogram.

The mole is used principally for chemicals. One mole of a substance is the amount that contains as many constituent particles as there are atoms in 12 gram of Carbon-12. This number of molecules is called Avogadro's number, and is approximately 6×10^{23} . Clearly, a mole of a material has a mass proportional to that of each particle. A mole of water has a mass of approximately 18 gram, and occupies about 18 cubic centimetres in normal room conditions. By the way, a cubic metre of water weighs approximately a tonne (1000 kg).

Luminosity is important to engineers who work with fibre optics and optoelectronics.

1.1.4 Physical Constants

The next table lists several **physical constants** of interest. Even if you cannot remember their values, you must learn their physical meanings, and it is advisable to memorise their orders of magnitude.

For example, Boltzmann's constant is a factor of proportionality between the heat energy of a typical particle of matter and the temperature of the material that the particles comprise. If you multiply Boltzmann's constant by Avogadro's number, then you obtain approximately 8.31 J/K, which is the gas constant R ; this concerns the energy in a mole of an ideal (non-interacting, indefinitely compressible) gas.

Constant	Value	Symbol
Speed of light (celeritus)	$2.9979 \times 10^8 \text{m/s}$	c
Boltzmann's constant	$1.38 \times 10^{-23} \text{J/K}$	k
Electron charge	$1.609 \times 10^{-19} \text{C}$	e
Permittivity of free space	$8.85 \times 10^{-12} \text{F/m}$	ϵ_0
Permeability of free space	$4\pi \times 10^{-7} \text{H/m}$	μ_0
Planck's constant	$6.626 \times 10^{-34} \text{J.s}$	h
Newton's universal constant of gravitation	$6.67 \times 10^{-11} \text{m}^3.\text{s}^2.\text{kg}^{-1}$	G

1.2 Measurement Categories

No doubt there are many ways to broadly classify measurement procedures. *Carr* slices them thus:

Direct: Measuring the desired quantity 'face-to-face', as it were. For example, using a ruler to measure the width of a bench.

Indirect: Measuring a second quantity from which the first may be inferred. For example, measuring the color of the sun and inferring its surface temperature.

Null: Balancing the desired quantity by a controllable source. For example, adjusting a calibrated resistor in a Wheatstone bridge until the current flowing between the two sides equals zero, then calculating the value of the unknown resistance in another of the arms. (See lecture 2 for bridge circuits.)

1.3 Average, Arithmetic Mean, Geometric Mean, Median, Mode

The term *average* can bear different meanings. In science and engineering, several of these meanings have been made precise.

The arithmetic mean of a set of quantities is their sum divided by the number of terms in the sum: e.g., $amean(a, b) = (a + b)/2$ and $amean(a, b, c) = (a + b + c)/3$.

The geometric mean of n quantities is the n -th root of their product: $gmean(a, b, c) = \sqrt[3]{a.b.c}$.

In electronics, physics and mathematics, there are other kinds of mean, such as the theoretical mean value of a continuous quantity: for example the root mean square (rms) value of a sinusoidal waveform, which is defined using an integral formula.

Statistics, a field especially important to measurement (and to manufacturing), utilises the median and mode. The median of a set of quantities is the value with half of the set of values above it, and half of them below it. Evidently, the median makes sense only for *one* dimensional measurements!

The mode is the most frequent value. There can be more than one mode, especially when the set of values is few or sparsely spread.

1.4 Significant Figures

When quoting a value, we should not use either more or fewer figures than its precision justifies. For example, a mercury thermometer may tell us the temperature to the nearest degree Celsius, but it's doubtful whether it is manufactured precisely enough, or that we could read it well enough, to claim that it's now 23.4 degrees!

Also, don't place too much credence in the numbers that your calculator displays. If you've measured a quantity to two significant figures, for example a temperature of 23°C, then plugged it into a formula for the resistance of a temperature-sensitive conductor, then please don't trust the calculator's ten digit number! Only the first two digits have any chance of being accurate!

1.5 Error

1.5.1 Absolute and Relative Errors

Suppose that the precision is better than 1 degree, but worse than 0.1 degree. If we are confident (from knowledge and observation, not from vanity or imagination) that the temperature is between 23.2 and 23.8 degrees, then we should note the mean value and the error, and record the temperature (in °C) as the mean plus or minus the error: 23.5 ± 0.3 . In more precise terminology, this type of plus-or-minus error is called the *absolute error*.

The ratio of the absolute error to the mean quantity is called the *relative error*. When this is expressed as a percentage, this ratio is understandably called the *percentage error*.

1.5.2 Approximate Rules for Combining Errors

When adding or subtracting two quantities, their *absolute* errors add. However, when multiplying or dividing, their *relative* errors add.

As a rule of thumb, in combining quantities, errors only get worse, not better.

These approximate rules for error calculations assume that the quantities are statistically independent, so that a large series of measurements of all the quantities shows no correlation between them. In this situation, plotting one quantity against another shows a pattern that's fairly uniform in all directions out from the point described by the two mean values.

An exception to the rules for combining errors can occur when quantities are highly correlated: as an obvious example, irrespective of the errors in our measurement, if T is the current temperature then $T - T$ is always zero exactly. However, independence is often a reasonable initial working hypothesis.

1.6 "Goodness" of Measurements

Carr, sections 2-5 to 2-7, pages 31 to 39.

The correctness of measurements is not to be taken for granted. A single measurement may be untrustworthy for a number of reasons, to do with the source of the measured quantity, the instrument, the environment, and ourselves.

We can gain a better appreciation of the influences on our measurements by repeating them in identical, similar, or very different conditions, and at small and long intervals. Terms describing relevant factors include the following.

Error: The difference between the reported value and the (usually unknown) true value of a quantity.

Validity: How well an instrument (or measurement technique) reflects what it is purported to measure. Depends on details of the instrument, and varies with the operating conditions.

Robustness: When the input to an instrument varies slightly, does its output stably reflect the changes, or does it become unstable, or chaotic?

Reliability: Given very different values, or measurements taken at very different times, are the measurements consistent?

Repeatability: Do repeated measurements, on a constant true value, give the same answer?

Accuracy: How close is the mean measurement of a series of trials to the true value?

Precision: How much do the measurements vary from trial to trial?

Resolution: How finely can we and/or the instrument separate one value from another that's close to it?

Mistake: "Human error"!

Errors are to be expected; they are intrinsic in the physical processes of measurement making. *Carr*, section 2-7 lists four categories of measurement errors and some subcategories, as follows.

1. **Theoretical errors:** The explicit or implicit model on which we base our interpretation of our measurements may be inapplicable or inaccurate.

(a) **Range of Validity:** A model is applicable only within a limited range of conditions. Beyond that, it will give inaccurate predictions.

(b) **Approximation:** Models have finite precision even within their range of validity. Don't quote ten significant figures when only two are trustworthy.

2. **Static errors:** A very broad category!

(a) **Reading errors:** Due to misreading, or a difficulty in accurately reading, the display of the instrument.

i. **Parallax:** Analog meters use a needle as a pointer to indicate the measured value. Reading this at an oblique angle causes a misreading, known as a **parallax reading error**.

ii. **Interpolation:** The needle often rests between two calibrated marks. Guessing its position by interpolation is subject to an error that depends on the size of the scale, and on the visual acuity and experience of the person reading the meter.

iii. **Last-digit bobble:** Digital readouts are often observed to oscillate between two neighbouring values, for example a digital voltmeter (DVM) may alternately show 3.455 and 3.456 volts. This occurs when the actual value is about midway between the two displayed values. Small variations in the system under test, or in the meter itself, are sufficient to change the reading when it is delicately poised between the two values.

(b) **Environmental errors:** Measurements can be affected by changes in ambient factors.

i. **Temperature.**

ii. **Pressure.**

iii. **Electromagnetic (EM) fields:** Static electric or magnetic fields, dynamic (changing) fields, and propagating fields (radiation) can interfere with measurements. A particularly common example is the mains electricity supply, which is ideally a sinusoid; in Australia this is specified to have a frequency of 50 Hz. In reality, mains power is not a pure sinusoid, so it contributes interference at other frequencies also.

(c) **Characteristic errors:** Static errors intrinsic to the measuring instrument or process. Physical limitations and manufacturing quality control are factors in several characteristic errors. Incorrect calibration can also contribute!

- i. **Manufacturing Tolerances:** Design and manufacturing processes are frequently inexact. For example, the calibrated marks on a ruler are not 1.0000 millimetres apart. Hopefully some will be slightly above and some slightly below, so that over a series of measurements these errors will be **random** and so balance out, but they might not — the errors in the manufacturing process of one or more batches of rulers might be **systematically biased**.
 - ii. **Zero Offset:** a meter (for example) may read zero when the actual value is nonzero. This is a common form of *calibration error*.
 - iii. **Gain error:** amplifiers are widely used in instruments such as CRO probes, and we may trust that “times 10” means precisely what it says only when the amplification has been carefully calibrated.
 - iv. **Processing error:** modern instruments contain complex processing devices such as analog computers which can introduce errors into the process leading to the displayed value of a measurement. Digital devices have finite precision (see *quantization errors*, below) and are occasionally wrongly programmed: a small programming error often produces large errors in the results.
 - v. **Repeatability error:** instruments change over time, which is why they must be regularly calibrated, just as a car must be serviced. Instruments change, however slightly, even between consecutive measurements. The act of measurement itself may affect the instrument, for example spring scales lose some elasticity with every use.
 - vi. **Nonlinearity:** ideally, an instrument designed to be **linear** has an output which is proportional to its input, but this is only *approximately* true, and then only within a *range of validity*. Drive an amplifier to too high a gain and it will operate in its nonlinear regions, producing a severely distorted output signal.
 - vii. **Hysteresis:** Some measurement systems remember some of their past history, and produce different results if a different path is taken to the same final set of external conditions.
 - viii. **Resolution:** devices can only **resolve** (that is, distinguish) values that are sufficiently separated. For example, optical instruments cannot easily resolve objects less than one wavelength apart.
 - ix. **Quantization:** When analog values are recorded on a digital system (**analog to digital conversion**), the values are rounded to the nearest available step.
3. **Dynamic errors:** Due to the measured quantity changing, or the measured object moving, during measurement. *Carr* mentions two kinds of dynamic errors.
- (a) **Mechanical:** Such as the inertia of the needle of an analog meter.
 - (b) **Electronic:** For example, a sample and hold circuit with a long time constant, used in an attempt to record a high frequency sine wave.
4. **Insertion errors:** We wish to know the values that quantities have in a system when the measuring instrument is absent, but of course we can only with the instrument present, and that constitutes a different system! The values can differ between the two systems, because the effect of the instrument is never zero, and may not be negligible!
- (a) **Classical insertion error:** An example is the use of a voltmeter with a low resistance compared to the component or subsystem across which it is connected. Another is an ammeter with a large resistance compared to the current loop in which it is placed.
 - (b) **Quantum insertion error:** The theory of quantum physics places restrictions on the precision with which certain quantities may simultaneously be measured (Heisenberg Uncertainty Principle). In optics this can be a significant concern. On the other hand, we don't expect the HUP to worry us much in the Electronic Measurements and Instrumentation laboratory classes.

1.7 Dealing with Errors

Carr, sections 2-8 and 2-9, pages 39 to 41.

To minimise measurement errors, one may improve the procedure, or one may use statistical averaging.

Procedural improvements may include using more accurate instruments, in particular meters that cause less disturbance to the system being measured, for example a voltmeter with an impedance that is much higher than that of the circuit under test.

Statistical averaging involves attempting the same measurement on different occasions, or by using different instruments — for example by measuring the current in a loop using several ammeters in series and reading them at the same time.

References

It is intended that the lecture and laboratory notes suffice when preparing for this subject's examination.

If you wish to investigate any of the topics further, any of a variety of related texts may be found useful, but for the record, the lecturing material is largely based on material from these texts:

1. *Elements of Electronic Instrumentation and Measurement*, Third Edition, by Joseph J. Carr, published by Prentice-Hall, 1996.
2. *Principles of Electronic Instrumentation and Measurement*, by Howard M. Berlin and Frank C. Getz, Jr., published by Macmillan, 1988.
3. *Modern Dictionary of Electronics*, Sixth Edition, by Rudolf F. Graf, published by Howard W. Sams & Co., Inc., in the early 1980's.

We will cite Carr's work the most often, but its text is filled with egregious typographical errors despite having had three proof-readers.

Berlin and Getz's book is commendable but appears to be out of print.

As with all dictionaries, the brief definitions given in Graf's do not do justice to the terms. Without some prior acquaintance, it's easy to get the wrong impression. Also, more relevant to current technology would be Graf's Seventh Edition, published in 1999.